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1380141

THE UNITED STATES OF AMERICA

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United States Patent and Trademark Office

October 17, 2005

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APPLICATION NUMBER: ***60/558,298***
FILING DATE: ***March 30, 2004***
RELATED PCT APPLICATION NUMBER: ***PCT/US04/40460***

UNITED STATES PATENT AND TRADEMARK OFFICE
DEPARTMENT OF COMMERCE

Certified by

Jon W. Dudas

Under Secretary of Commerce
for Intellectual Property
and Director of the United States
Patent and Trademark Office

13049 U.S. PTO
033004

19249 U.S. PTO
60/558298
033004

PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. ER 542082551 US

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
John G.	DeSteese	Kennewick WA, 99336

Additional inventors are being named on the 1 *separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max)

Methods and Applications for Ambient Energy Harvesting

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

☑ Customer Number: 29171

OR

☐ Firm or Individual Name					
Address					
Address					
City		State		Zip	
Country		Telephone		Fax	

ENCLOSED APPLICATION PARTS ***(check all that apply)***

☑ Specification *Number of Pages* 51
☑ Drawing(s) *Number of Sheets* 30
☐ Application Data Sheet. See 37 CFR 1.76
☐ CD(s), Number ______
☐ Other (specify) ______

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☑ Applicant claims small entity status. See 37 CFR 1.27.
☐ A check or money order is enclosed to cover the filing fees.
☑ The Director is herby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 02-1275
☐ Payment by credit card. Form PTO-2038 is attached.

FILING FEE Amount ($): 80.00

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☑ No.
☐ Yes, the name of the U.S. Government agency and the Government contract number are: ______

Respectfully submitted,

SIGNATURE James D. Matheson

TYPED or PRINTED NAME James D. Matheson

TELEPHONE (509) 375-3782

Date 3/30/04

REGISTRATION NO. 54,569
(if appropriate)
Docket Number: 13664-B PROV CIP

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

PROVISIONAL APPLICATION COVER SHEET
Additional Page

PTO/SB/16 (08-03)
Approved for use through 07/31/2006. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

Docket Number 13664-B PROV CIP

INVENTOR(S)/APPLICANT(S)

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Number 1 of 1

13049 U.S. PTO
033004

FEE TRANSMITTAL for FY 2004

Effective 10/01/2003. Patent fees are subject to annual revision.

☑ Applicant claims small entity status. See 37 CFR 1.27

TOTAL AMOUNT OF PAYMENT ($) 80.00

Complete if Known	
Application Number	Not yet assigned
Filing Date	Herewith
First Named Inventor	John G. DeSteese
Examiner Name	Not yet assigned
Art Unit	Not yet assigned
Attorney Docket No.	13664-B PROV CIP

METHOD OF PAYMENT (check all that apply)

☐ Check ☐ Credit card ☐ Money Order ☐ Other ☐ None

☑ Deposit Account:

Deposit Account Number: 02-1275

Deposit Account Name: Battelle Memorial Insitut

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FEE CALCULATION

1. BASIC FILING FEE

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description	Fee Paid
1001	770	2001	385	Utility filing fee	
1002	340	2002	170	Design filing fee	
1003	530	2003	265	Plant filing fee	
1004	770	2004	385	Reissue filing fee	
1005	160	2005	80	Provisional filing fee	80.00

SUBTOTAL (1) ($) 80.00

2. EXTRA CLAIM FEES FOR UTILITY AND REISSUE

			Extra Claims		Fee from below		Fee Paid
Total Claims		-20** =		X		=	
Independent Claims		- 3** =		X		=	
Multiple Dependent						=	

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description
1202	18	2202	9	Claims in excess of 20
1201	86	2201	43	Independent claims in excess of 3
1203	290	2203	145	Multiple dependent claim, if not paid
1204	86	2204	43	** Reissue independent claims over original patent
1205	18	2205	9	** Reissue claims in excess of 20 and over original patent

SUBTOTAL (2) ($) - 0 -

**or number previously paid, if greater; For Reissues, see above

FEE CALCULATION (continued)

3. ADDITIONAL FEES

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description	Fee Paid
1051	130	2051	65	Surcharge - late filing fee or oath	
1052	50	2052	25	Surcharge - late provisional filing fee or cover sheet	
1053	130	1053	130	Non-English specification	
1812	2,520	1812	2,520	For filing a request for *ex parte* reexamination	
1804	920*	1804	920*	Requesting publication of SIR prior to Examiner action	
1805	1,840*	1805	1,840*	Requesting publication of SIR after Examiner action	
1251	110	2251	55	Extension for reply within first month	
1252	420	2252	210	Extension for reply within second month	
1253	950	2253	475	Extension for reply within third month	
1254	1,480	2254	740	Extension for reply within fourth month	
1255	2,010	2255	1,005	Extension for reply within fifth month	
1401	330	2401	165	Notice of Appeal	
1402	330	2402	165	Filing a brief in support of an appeal	
1403	290	2403	145	Request for oral hearing	
1451	1,510	1451	1,510	Petition to institute a public use proceeding	
1452	110	2452	55	Petition to revive - unavoidable	
1453	1,330	2453	665	Petition to revive - unintentional	
1501	1,330	2501	665	Utility issue fee (or reissue)	
1502	480	2502	240	Design issue fee	
1503	640	2503	320	Plant issue fee	
1460	130	1460	130	Petitions to the Commissioner	
1807	50	1807	50	Processing fee under 37 CFR 1.17(q)	
1806	180	1806	180	Submission of Information Disclosure Stmt	
8021	40	8021	40	Recording each patent assignment per property (times number of properties)	
1809	770	2809	385	Filing a submission after final rejection (37 CFR 1.129(a))	
1810	770	2810	385	For each additional invention to be examined (37 CFR 1.129(b))	
1801	770	2801	385	Request for Continued Examination (RCE)	
1802	900	1802	900	Request for expedited examination of a design application	

Other fee (specify) ____________

*Reduced by Basic Filing Fee Paid

SUBTOTAL (3) ($) - 0 -

SUBMITTED BY			(Complete *(if applicable)*)	
Name *(Print/Type)*	James D. Matheson	Registration No. (Attorney/Agent)	54,569	Telephone 509-375-3782
Signature	James D. Matheson			Date 3-30-04

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	)	
	)	
John G. DeSteese, et al.	)	
	)	
	)	
For: METHODS AND APPLICATIONS FOR AMBIENT ENERGY HARVESTING	)	Our Ref. No: 13664-B PROV CIP
	)	Date: March 30, 2004

CERTIFICATE OF MAILING

Mail Stop Provisional Application
Commissioner for Patents
Alexandria, Virginia 22313-1450

Dear Sir:

The undersigned hereby certifies that the attached:

[X] Provisional Patent Specification of 51 pages, and
[X] 30 Figures of Included in Specification
[X] Fee Transmittal (2 ea.)
[X] Provisional Application for Patent Cover Sheet
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Janice K. Laybourn
Signature

3/30/04
Date Deposited

Janice K. Laybourn K1-53
Intellectual Property Services
Battelle Memorial Institute
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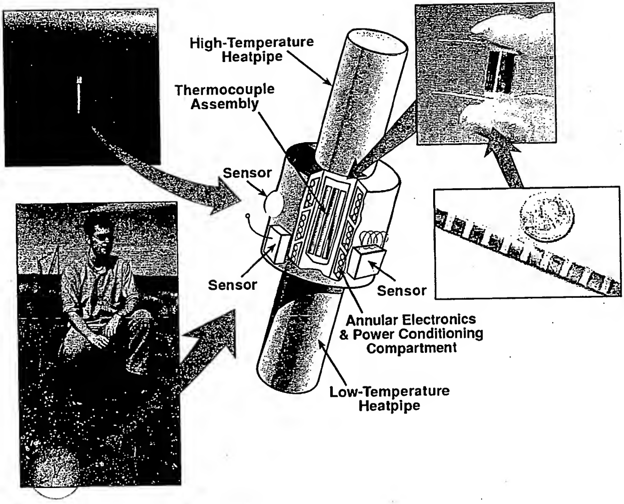
Richland, WA 99352
(509) 375-2566



This is a typical conceptual assembly of the Thermoelectric Ambient Energy Harvester comprised of the generator (thermocouple assembly), heat delivery and rejection components (heat pipes), sensors being powered (not necessarily shown to scale), and interfacing electronics. The Thermoelectric Ambient Energy Harvester can produce enough power from small ambient differences in temperature (<5°C) to power a variety of sensors and other low-power applications in the 100 microwatt to 100-milliwatt range. Deployment of the Ambient Harvester is shown in two environments where natural temperature differences exist: above and below the ground surface and either side of ductwork that delivers heating, ventilation, and air conditioning in buildings.

9. **Product's primary function:**

A radically new thermocouple design by PNNL allows us to literally pull useful amounts of thermal energy out of the air to power sensors and the radio frequency transmitters necessary to send the data they generate for a wide range of remote monitoring applications including building energy management, automotive component controls, agricultural monitoring, security surveillance, and wildlife management.

The Thermoelectric (TE) Ambient Energy Harvester uses an assembly of ultra-thin thermocouples in a unique configuration that can exploit small (>2°C) temperature differences occurring naturally in the environment (e.g., ground to air, water to air, skin to air) to provide maintenance-free, continuous power for wireless sensors and a wide range of other stand-alone, low-power devices

The individual thermocouples, which are typically 1 cm high by 1.5 cm wide and only a few micrometers thick, are deposited in a linked "chain" onto a thin, flexible plastic substrate (similar to camera film), using a sputtered thin-film deposition technique developed by PNNL. This plastic substrate is coiled around a spool enabling up to several thousand thermocouples to be assembled into a thermoelectric generator about 1 x 1.5 cm that can produce tens of microwatts to 100 milliwatts or more.

PNNL is developing applications for the TE Ambient Energy Harvester product in a building energy management project sponsored by the U.S. Department of Energy. Other applications are currently anticipated in many areas including automotive performance monitoring, homeland and military security and surveillance, biomedicine, and wilderness area and agricultural management.

Heat-gathering and heat-rejecting subsystems, such as heat pipes containing condensable fluids, can be coupled to the "hot" and "cold" surfaces of the TE Energy Harvester (see Figure 1) to extend the thermal "reach" of the generator by several centimeters to areas where temperature differences may be larger than those found in the device's immediate environment. One or both sides of the generator can be heated or cooled by other heat transport methods such as conduction, convection, or radiation. Temperature differences of as little as 5°C will activate the generator for useful energy output, and power production with even smaller differences (1 or 2°C) is possible. Larger temperature differences will produce correspondingly larger outputs. Additionally, the thermocouple can work both ways: i.e., if the "cold" side of the harvester is in the ground, the end exposed to air will be the "hot" side during the day. At night when the air is cooler, the thermocouple will still generate power, enabling power production around the clock. The TE generator can operate in extreme temperature environments, as cold as -100°C and as hot as +250°C.

The generator produces electricity as a result of the Seebeck effect, which is common to all thermoelectric devices. This effect directly converts heat into electricity by maintaining a temperature difference between junctions of dissimilar metals or p- and n-type semiconductors (Figure 2). The latter are preferred because they produce higher output per unit of temperature difference. As Figure 2 shows, heat available at the hot surface, T_H, flows down both thermo elements N and P to the cold surface maintained at temperature T_C by a heat sink (i.e., a means of removing heat from the system). The difference in temperature causes a flow of electrons and "holes" (equivalent to positively charged electrons) which, in turn, develops a voltage across the electrically resistive load. This voltage causes current flow that delivers power to the load. A single junction of such materials is known as a thermocouple. The maximum output voltage (V) generated by a number of thermocouples (n) connected in series is given by:

$$V = n \cdot S \cdot \Delta T$$

where S is the Seebeck coefficient of the couple (in volts/°C) and ΔT is the temperature difference ($= T_H - T_C$ in °C) maintained across the thermocouple array. The Seebeck coefficient of the TE materials used in this product is about 300 microvolts/°C.

To obtain useful voltages (≥1 volt) from a TE generator exposed to small temperature differences requires a large number of thermocouples in the assembly. Conventional TE generators are assembled from discrete

elements as illustrated in Figure 3. Because they are freestanding, the practical ratio of length to cross-section (L/A) is typically in the range 10 to 30 cm^{-1} as shown. Figure 4 shows the number of thermocouples needed to achieve various power output levels as a function of L/A for the bismuth telluride thermocouple system. The figure also plots lines of constant voltage. Voltages of 1 V or higher are needed to activate the silicon-based semiconductors that power sensors and associated microprocessors and circuitry. Figure 4 shows that conventional discrete-element TE devices with L/A ratios under 30 cm^{-1} cannot provide adequate voltage for such applications at typical ambient temperature differences.

Because our thermocouples are deposited on a supportive substrate, we are able to make them extremely thin in comparison to their length, thus achieving the high L/A geometry of 1,000 to 10,000 cm^{-1} necessary to produce useful voltage outputs. Our thermocouples are composed of p- and n-type elements based on alloys of bismuth telluride and antimony telluride deposited as a thin film (<10 μm thick) on a polyimide substrate (see Figure 5). The deposition is conducted with high integrity in a clean noble gas (argon) environment and initially processed under high vacuum conditions. The thermocouples can be produced in strips of any length from a few centimeters to ~ 80 meters (~ 260 feet).

The substrate provides a convenient way to handle and bundle large numbers of thermocouples. It also provides other benefits in terms of reliability and manufacturing simplicity. It provides a continuous physical support for each thermocouple and the connections between the thermocouples, in contrast to conventional discrete-element thermocouples where connections for the brittle, upright thermocouples must be made as a separate step in the manufacturing process and the connections themselves are more fragile and susceptible to deterioration (Figure 6). Although our thermocouples are produced in a continuous strip, we connect them in both series and parallel. This redundancy protects against the failure of individual elements. Thus, if one or even a few thermocouples failed randomly in service, the TE generator would continue to supply a large portion of its rated current and voltage.

The substrate does conduct heat that bypasses the thermocouple array, but this loss in efficiency is trivial in comparison with the substrate's value in enabling a thermocouple configuration that is much denser than is possible with freestanding discrete elements. And far from being an inefficient heat loss mechanism, the substrate, with its transverse thermal conductivity, actually helps "lock in" the temperature difference that activates the TE generator deposited on it. The loss of efficiency caused by the substrate would be a consideration in a TE generator designed for best possible energy conversion efficiency. However, such efficiency is much less significant at the low power ranges our product provides. In this case, we are not concerned about wasting energy because the "fuel supply" (temperature differences in the environment) is essentially infinite.

10A. Product's competitors:

In general, the TE Ambient Energy Harvester's principal competition comes from other TE generators that could provide similar energy conversion functions and from electrochemical batteries, which our product is designed to replace. One other company (D.T.S.) has announced it has produced a thin-film thermocouple and Seiko Instruments, Inc., has reported developing a micro-scale TE generator constructed from discrete-element thermocouples.

D.T.S. (Thin Film Thermoelectric Generator Systems) GmbH Köthener Str. 34, D-06118 Halle, Germany.

> This company has demonstrated and published details of TE generators constructed from thin films of bismuth telluride deposited on foils. No model number is evident.

Seiko Instruments Inc., 563 Takatsukashinden, Matsudo-shi, Chiba 270-2222, Japan.

> Seiko Instruments Inc. has reported the successful development of a microscale TE generator that powers a wristwatch from human body heat. No model number is evident.

Several manufacturers are producing thermoelectric devices; these differ dramatically from ours in their configuration. Theirs consist of discrete-element thermoelectric devices with low L/A ratios. These thermocouples are typically manufactured as heating and cooling elements. They operate in Peltier mode, which is the reverse of our product; electricity is sent through them to generate heat or cold rather than exposing them to heat and cold to produce electricity as ours does. Some manufacturers offer custom services to make their thermocouples power producers. However, the discrete element designs they use prevent them from achieving the high L/A ratios necessary to produce a usable amount of power at the low temperature differences that our design is able to exploit.

Melcor Corporation and Ferrotec America Corporation are two examples of companies manufacturing conventional, discrete-element TE devices. Cited model numbers are representative of a large product range and are the units we evaluated during the development of our product.

MELCOR Corporation, 1040 Spruce Street, Trenton, NJ 08648

- Model No. HT4-12-40. Dimensions: 40 x 40 x 4.1 mm; maximum operating temperature 225°C
- Model No. HT3-12-30. Dimensions: 30 x 30 x 3.2 mm; maximum operating temperature 225°C

Ferrotec America Corporation, 40 Simon Street, Nashua, NH 03060

- Model No. 95/00/007/018. Dimensions: 4 x 4 x 2 mm; maximum operating temperature 200°C
- Model No. 95/02/065/018. Dimensions: 12.1 x 11.1 x 2.34 mm; maximum operating temperature 200°C

Our thermoelectric ambient energy harvester is designed to replace batteries in low-power, long-life applications. The state-of-the-art of competitive batteries is represented by the following:

Ultralife Batteries, Incorporated, 2000 Technology Parkway, Newark, NY 14513

- Lithium-Manganese Dioxide Battery, Model UB2519 Voltage 3 V; Capacity 1300 mAh; weight 22 g; temperature range -30 to +72°C

Hitachi Maxell, Ltd. 2-8-12, Iidabbashi. Chiyoda-ku, Tokyo 102-8521, Japan

- Lithium Thionyl Chloride Battery, Model ER17/50H Voltage 3.6 V; Capacity 3300 mAh; weight 20 g; temperature range -40 to +85°C

10B. Product comparison (matrix):

Product Feature	TE Ambient Energy Harvester	D.T.S. Thin-Film TE Generator	Seiko Wrist Watch TE Generator	Conventional Discrete Element TE Generator	Lithium Batteries	Competitive Advantage
Adequate output voltage without DC/DC voltage amplification	**Yes**	Yes	No	No	Yes	Output quality matches all the competition and is superior to discrete element units
Life with 50 μW average load	**Infinite**	Unknown	Unknown	Infinite	7 to 9 years	Projected life longer than all except discrete element units
Life with 1 mW average load	**Infinite**	Unknown	Unknown	Infinite	12,000 hr (1.36 years)	Projected life longer than all except discrete element units
Probable life limiting cause	**Application lifetime or obsolescence**	Internal interconnection aging or failure	Internal interconnection aging or failure	Internal interconnection aging or failure	Discharge or internal structural failure	Most likely to survive for lifetime of application
Integrated heat transfer structures	**Yes**	No	Yes	No	Not Applicable	Most adaptable to wide range of ambient conditions
Operating Temperature Range (°C)	**-100 to +250 No materials used that diffuse into PN junctions**	+100 Diffusion of braze materials may poison thermocouples	unknown (operates near ambient in application)	<225[1] generally. Diffusion of braze materials may poison thermocouples	-40 to +85	Superior to batteries and the best of competitive TE products. No thermocouple poisoning possible
Application versatility	**Continuous strip thermocouple fabrication**	Generators must be custom assembled	Generators must be custom assembled	Generators must be custom assembled	Not Applicable	Application tailoring achieved simply by varying number of thermocouples, deposition parameters, and strip length

Matrix (contd)

Product Feature	TE Ambient Energy Harvester	D.T.S. Thin-Film TE Generator	Seiko Wrist Watch TE Generator	Conventional Discrete Element TE Generator	Lithium Batteries	Competitive Advantage
Cost ($/unit)	1 to 20 projected with volume production. Cost dependent on application integration requirements	Unknown	Unknown but reported anecdotally to be high enough to negatively impact marketability of watch application	15 to 25	4 to 10	Cost somewhat proportional to power is less than competition at low end of power range (1µW to 100µW)
Manufacturing simplicity	Can be produced in continuous strip on flexible substrate, only two connections in assembly for any application	Numerous connections needed to bundle a large number of thermocouples	Numerous connections needed to bundle a large number of thermocouples	Numerous connections needed to bundle a large number of thermocouples	Established automated battery assembly	Design and manufacturing simplicity improves reliability, decreases likelihood of manufacturing defects and inservice failure
Environmental considerations	No special handling and disposal concerns	No special handling and disposal concerns	No special handling and disposal concerns	No special handling and disposal concerns	Lithium cells are potentially hazardous if mishandled, opened or exposed to temperatures typically >100°C	Environmentally benign. As good as or superior to any other TE generator and superior to batteries.
Typical upper operating temperature limit for discrete element thermocouples is 150 to 200°C; however, we found one advertised with an exceptional high-temp capability of 250°C.						

10C. Product improvements:

The TE Ambient Energy Harvester provides a zero-maintenance source of electric power for the lifetime of the application, generated right where it is needed. It enables wireless sensors to be essentially self-powered and replaces batteries and hard-wired alternative power solutions. Ambient harvesters are the ideal solution for powering sensors and monitors in remote, difficult-to-reach places and also in relatively accessible applications where the cost, reliability, and complexity of battery and/or hardwire solutions are not economic. Our product draws thermal energy directly from the local environment of the application using engineered heat gathering and dissipation components. This level of energy production and integration in the microwatt-to-milliwatt power range has been investigated by few commercial competitors.

Technically, the closest competition to our product is the TE generator assembly reported in the literature by D.T.S. This device uses the same thermocouple system (bismuth telluride) as our product. D.T.S. deposits p- and n-type semiconductors on thin foils, an additional similarity. The contrast between the products is in the method and configuration of assembly. We assemble our generator as a continuous strip of series- or series/parallel-connected thermocouples deposited on a flexible supporting substrate. D.T.S. reports that they deposit thermocouples on individual flat foils and assemble these into a generator in a configuration resembling a deck of cards. This requires delicate interconnections to be made between and across foil edges to connect all elements of the generator. We project that these interconnections add cost to the assembly and are vulnerable to damage, aging, and general deterioration. Our continuous strip configuration requires external connections only at its two terminal ends. A single strip constructed in our configuration can contain hundreds to thousands of deposited thermocouples without additional connectors between subsets. In addition, our thermocouples are deposited on a thin, flexible substrate with a thickness of only a few micrometers. This allows them to maintain adherence and connectivity when the strip is wound around spindles as small as 2 mm in diameter. This spooled configuration allows us to generate usable amounts of power (up to 100 mW) from tightly packed bundles of up to a thousand or more thermocouples with very small overall dimensions. D.T.S. offers services to prepare special materials to client specifications and to assist in research and development activities under contract. However, the TE generators they describe do not appear to be available as a line of cataloged commercial products with quotable prices.

Seiko reports the development of a micro-scale version of a conventional TE generator composed of discrete bismuth telluride elements. They report the manufacture of several TE modules

containing between 102 and 250 thermocouple elements in sizes up to 3 x 3 x 1.3 mm. They also succeeded in integrating a yet-smaller TE generator into a wristwatch and powering it with human body heat emitted through the skin. However, their TE generator is used to recharge a lithium ion battery in the watch. Thus it is not used as the sole power source, and their application remains vulnerable to the disadvantages of battery power that our product eliminates. PNNL's ambient harvester is designed to provide the sole source of power for remote and even unretrievable applications. While our concept also requires a form of energy storage to compensate for the moment-to-moment variability of an ambient energy supply, we favor and have demonstrated adequate carry-through using supercapacitors. Seiko claims to have marketed the TE-powered wristwatch in 1998; however, it does not appear to be a catalog item currently.

PNNL's ambient harvester can tolerate a wider operational and storage temperature range than electrochemical batteries (-100 to +250°C versus -40 to +85°C) and has greater reliability than batteries because it derives its power from temperature differences in its environment (an essentially unlimited "fuel" source). It eliminates concern about battery reliability and avoids the cost and logistic difficulty of replacing batteries. Our ambient harvester's solid-state design and use of environmentally benign materials provide greater durability and safety and easier end-of-life disposal than are offered by electrochemical batteries.

There are companies (e.g., Melcor, Ferrotec, etc.) that produce conventional TE generators for heating and cooling applications who offer custom services to design and build systems thermocouples to produce electricity. The conventional thermocouples these companies produce differ radically from ours in design and configuration, in ways that make their product more difficult to produce reliably, more susceptible to damage, and incapable of producing the power output ours can achieve with the same number of thermocouples. One conventional thermoelectric generator comprised of 100 discrete thermocouples would typically require at least 200 soldered or brazed connections. Because our design consists of sputter depositing the thermocouples onto a substrate, connections between the thermocouples are achieved as part of the deposition process, so there are only two "external" connections – one at each end of the "chain" of thermocouples (and these are not adhered with brazing) - resulting in far fewer points or nodes susceptible to failure or aging and no chance of braze poisoning.

Specific integrated competitive power-producing products do not appear in the catalogs of other companies. No off-the-shelf thermocouple assemblies are currently available that match our L/A ratio and therefore the voltage output we are able to achieve with environmentally available temperature differences.

11A. Principal applications:

The TE Ambient Energy Harvester provides 24/7, long-lasting power enabling the use of wireless sensors in remote, hard-to-access locations for detection, identification, monitoring, and diagnostics. Principal applications being pursued by PNNL with government and industry are

- powering sensors for the future generation of smart buildings, particularly in the area of advanced energy management
- providing the automotive industry an alternative to batteries for on-board condition sensors, diagnostics, and alarms in vehicles.

In both areas, the applicability, performance, and life of wireless sensors are typically limited by battery characteristics and accessibility considerations. Even where a power grid connection is possible (as in buildings), the complexity and cost of the necessary wiring prohibit many sensor applications. Our product eliminates such constraints by cost-effectively providing a perpetual, autonomous source of electricity that can be integrated with the sensor.

11B. Other applications:

The Ambient Energy Harvester's small size and battery-free nature make it ideally suited for a wide range of applications in the rapidly growing area of wireless sensors:

- Military - sensors for weapons proliferation control, battlefield operations, intelligence gathering, safeguards and security activities, etc.
- Law enforcement - remote monitoring, surveillance, intrusion detection, movement sensing, material accountability, smuggling, etc.
- Homeland security – intruder sensing, detection, and alarming, border security, chemical/biological weapons detection in mailboxes, post offices, public transport, buildings, etc.
- Hospitals - pathogen detectors in HVAC systems and corridors, patient monitoring
- Agriculture - monitoring soil, water delivery, fertilizer and pesticide distribution, etc.
- Wildlife management – tracking threatened and endangered species
- At-home health care – body heat activated prosthetics, monitors, and hearing aids.
- Communications/convenience/vanity items - body heat-powered wristwatches, communication equipment, electric jewelry, cell phones, computers, etc.
- Infrared/radar radiation detectors - used in a variety of civilian and military applications
- Museums – humidity, heat, and light sensors
- Safety – personal tracking devices for climbers, backpackers, children, pets etc.

12. Summary:

Imagine pulling power out of thin air. PNNL's Thermoelectric Ambient Energy Harvester does just that. Incorporating a quantum leap improvement in thermocouple fabrication and assembly, the device is able to exploit naturally occurring temperature differences as low as 2°C. This product produces usable amounts of electric power to run wireless sensors and the radio frequency transmitters that send the data they collect to users anywhere in the world.

Think of them as miniature power plants, producing electricity right where it's needed 24/7 with no batteries to replace, no fuel supply to worry about, no moving parts to fix, no transmission and distribution lines to maintain, and no polluting emissions to deal with.

Its maintenance-free operation, tiny size, ability to tolerate wide temperature extremes, and capacity for powering radio transmitters, make the TE Ambient Harvester an ideal solution for powering sensors in remote or difficult-to-reach places and also in places where the alternative hardwire solution is not economic. The Harvester can power remote sensors that could alert a diabetic if her blood sugar's too high, tell a farmer if his field needs more fertilizer, sound an alarm if intruders have entered remote storage buildings, tell an HVAC system to open the damper in one office and close the damper in the next, alert a manufacturer to problems on a production line, power LED lights in remote third-world villages, run anthrax and nuclear weapons detection sensors on railroad box cars and shipping containers, or track endangered gorillas. They could power airborne instrumentation, water pollution monitors on an alpine lake, vehicle sensors along a highway in the Iraqi desert, temperature monitors on your SUV's right rear brakes, or a tracking device on Fido's collar.

There are literally thousands of uses for these tiny power producers. In volume production, their cost is likely to be low enough to allow their use even in vanity items and toys.

ORGANIZATION DATA

13. **Contact person to handle all arrangements on exhibits, banquet, and publicity:**

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Appendix – Supporting Information

Attachment 1: "Pros & Cons of Wireless" by Michael Kintner-Meyer and Michael R. Brambley, PNNL, in ASHRAE Journal, Nov. 2002, pp. 54-59. Article describing benefits and economics of wireless sensor technology for building energy management.

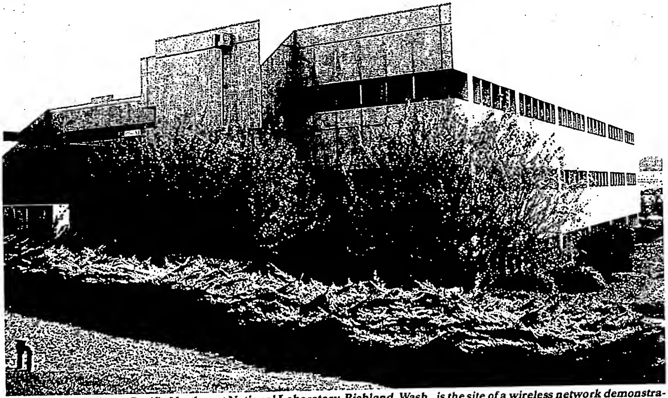
Attachment 2: "Sensor Power from Ambient Energy," by John G. DeSteese and Larry C. Olsen, PNNL. Article describing Thermoelectric Ambient Energy Harvester development in Pacific Northwest National Laboratory's Laboratory Directed Research and Development 2002 Annual Report.

Attachment 3: "Sensor Power from Ambient Energy" by John DeSteese, Larry Olsen, Tim Peters, Jim Skorpik and Juan Valencia, PNNL. PowerPoint presentation to potential automotive industry client describing the Thermoelectric Ambient Energy Harvester.

Attachment 4: "Technology Development: Wireless Sensors and Controls." Excerpt from Statement of Work from PNNL to US Dept of Energy, Building Technologies Program, describing development of building energy management sensors to be powered by the Thermoelectric Ambient Energy Harvester.

Attachment 5: "Thermoelectric Ambient Energy Harvester," A White Paper by John DeSteese, PNNL, for the Defense Logistics Agency, describing development of the Thermoelectric Ambient Energy Harvester for military applications.

Attachment 1



This office building at Pacific Northwest National Laboratory, Richland, Wash., is the site of a wireless network demonstration project sponsored by the U.S. Department of Energy.

Pros & Cons of Wireless

By **Michael Kintner-Meyer, Ph.D.,** Member ASHRAE, and **Michael R. Brambley, Ph.D.,** Member ASHRAE

The proliferation of cell phones, wireless computer networking, and wireless personal digital assistants has been phenomenal in the last few years. However, the building controls industry has not yet seen many wireless devices deployed in the field. Experts agree that the driver for deployment of wireless sensors will be cost advantages and the flexibility to relocate thermostats and sensors as the interior building layout adapts to the changing needs of the tenants and occupants.[1]

For any new technology to penetrate the marketplace, it either must be significantly less expensive than the existing technology, or it must have additional features that provide a competitive advantage and justify the same cost as the technology to be replaced. While mobility is a compelling driver for the impressive inroads of wireless technologies in the communication and computer networking markets, the need for mobility in building control remains limited. This means that wireless technologies must compete predominantly on the basis of cost.

Wireless Technologies

Commercially available generic wireless data acquisition hardware can be used for sensing conditions in buildings

About the Authors

Michael Kintner Meyer, Ph.D., and **Michael Brambley, Ph.D.,** are researchers at the Pacific Northwest National Laboratory, Richland, Wash., which is operated for the U.S. Department of Energy by Battelle Memorial Institute.

and HVAC systems. Wireless computer networking hardware components also can be adapted for sensor data collection for buildings. The essential components of a wireless data acquisition system (*Figure 1*) include: sensors; signal conditioners to convert the sensor signal to a sufficiently strong and clean digital signal; a transmitter for each sensor, for each signal conditioner, or shared by several signal conditioners; repeaters when needed; a receiver; and a connection to a processor where data are analyzed or processed using control algorithms.

Transmitters may be powered by electrical wiring in the building or by battery, depending on the availability of electrical connections at sensor locations. In addition to wireless data acquisition components, wireless systems specifically for building applications are beginning to emerge.

An informal survey of vendors of wireless data acquisition equipment found that receivers range from \$300 to \$1995; transmitters cost \$68 to \$1775 and repeaters cost more than \$250. Generally, costs are higher for wireless technology that communicates over greater distances and uses more sophisticated signal encoding to ensure successful signal transmission. Of the components, receivers generally are the most expensive. However, one receiver might serve many transmitters.

Maximum transmission distances range from as little as 30 ft (9 m) to as much as many miles. In general, interference is overcome and transmission distances extended by the addition of signal repeaters. When manufacturers configure wireless components into application-specific systems, often the costs of the integrated systems are lower than the sum of the costs for the individual components (except for highly specialized applications).

Two demonstration systems that apply existing radio frequency (RF) wireless technology to building and HVAC monitoring (and ultimately control) are described in the section that follows, along with a comparison of their costs and the costs of similar wired systems.

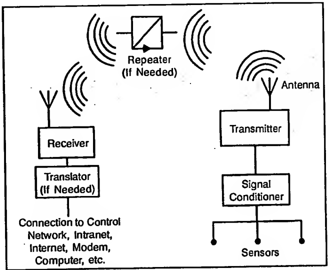


Figure 1: Primary components of a generic wireless radio frequency data acquisition system.

Demonstration Projects

In-Building Central Plant Retrofit

The demonstration building is a three-story heavy steel-concrete office building with a total floor area of about 70,000 ft^2 (6500 m^2). It is located on the campus of Pacific Northwest National Laboratory (PNNL). The HVAC system consists of central cooling, boiler, and ventilation system with 100 variable-air-volume (VAV) boxes. The building automation system (BAS) controls the central plant and the lighting system. A wireless temperature sensor network with 30 temperature transmitters was installed to measure zone-air temperatures. The zone-air temperatures then are used as input for a chilled-water reset algorithm designed to improve the energy efficiency of the centrifugal chiller under part-load conditions and reduce the building's peak demand without significantly increasing the energy use by distribution fans.

Wireless Temperature Sensor Network

The wireless network consists of commercially available wireless temperature sensor technology including 30 battery-powered temperature transmitters, three repeaters, one receiver, and the beta version of the "Translator," a new product for integration of wireless temperature sensors with another vendor's wired building automation network.

The operating frequency of the wireless network is 902 to 928 MHz, which requires no license per FCC Part 15 Certification.[2] The technology uses spread spectrum frequency hopping techniques to enhance the robustness and reliability of transmission. The transmitter has an open field range of 2,500 ft (760 m) and is battery-powered with a standard 3-volt $LiMnO_2$ battery with a nominal capacity of 1,400 mAh. The manufacturer estimates a battery life of up to five years with a 10-minute update rate. The transmitter has a battery test procedure with low-battery notification via the wireless network. This feature alerts building staff of the approaching end of the battery life through the building automation system. The repeater is powered by 120 Vac from the wall outlet with a battery backup. There are three repeaters, one installed on each floor. Because the repeater is line powered, the repeater operates at high power and provides up to 4 miles (6 km) of open field range. The receiver and the translator are installed in the mechanical room. The translator connects the receiver to the BAS bus.

An engineer performed an RF field strength survey for the building, in about four hours. The result of the RF survey was the recommendation of three repeaters, one for each floor of the building.

Wireless Sensors for Diagnostics

When the building engineer of the PNNL office building, was notified of heat buildup in the cafeteria's kitchen, he taped a wireless temperature sensor into the corner at the trouble spot.

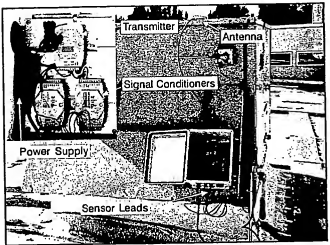


Figure 2: Demonstration of wireless rooftop data acquisition.

He monitored the temperature trends over a day, which showed that the original, wired temperature sensor for this zone was too far away from the trouble spot and that it, therefore, did not register the problem. He reprogrammed the EMCS to control for a weighted average of the original wired and the new wireless temperature measurements and, thus, solved the problem.

Rooftop Unit Application

The second part of the wireless project focuses on configuring, testing, evaluating and demonstrating wireless technology for use with packaged rooftop HVAC units. A system built from generic commercial components is shown in *Figure 2*.

Using wireless RF technology to collect data from packaged rooftop HVAC units relaxes some of the demands imposed by in-building applications of wireless communication. Equipment can be physically located so direct lines of sight are preserved and obstructions minimized. By positioning antennas above the roof, all transmitting antennas can "see" their corresponding receiving antenna. As a consequence, lower transmission power can be used, greater sources of interference can be tolerated, and communication protocols with less sophisticated means for ensuring reliable data transmission can be used. As a result, system and component costs likely are lower for rooftop wireless data acquisition than for in-building systems. Electrical power for data collection equipment generally can be provided at the packaged unit by tapping into the electrical power supplied for the HVAC unit.

Cost-Effectiveness

In-Building Temperature Sensor Example

The cumulative wiring distance for all of the temperature sensors is about 3,000 ft (900 m), with the majority of wiring being loose in-plenum. Sensor connections are assumed to be 18 AWG cable costing approximately $0.07/ft with a labor cost for installation of $1.53 per linear foot of wiring.[3] The cost comparison is shown in *Table 1*.

For simplicity, the labor cost for battery change-out, expected to occur every five years, is not included in *Table 1*. This activity can be estimated at about $300, assuming a battery cost of $3 per battery and two hours (at a rate of $100 per hour) of labor or just under $10 per sensor for replacing 30 batteries.

Cost Component	Cost: In-Building Temperature Sensor Network		Cost: Monitoring System For Three Packaged HVAC Units	
	Wired Design	Wireless Design	Wired Design	Wireless Design
Sensors	$1,800	$3,000[1]	$636	$636
Wiring	$4,800[2]	—	$68[3]	—
Communication and Signal-Conditioning Hardware	—	$2,475	$1,903	$1,500 – $5,900
Labor	—[4]	$800	$1,179[5]	$450
Total Cost	$6,600	$6,275	$3,786	$1,950 – $7,000
Average Cost Per Sensor	$220	$209	$316	$163 – $583

[1] Temperature sensors each with an integrated transmitter; [2] Including labor for installation; [3] Including conduit; [4] Included in cost of wiring; [5] Including installation of conduit.

***Table 1:** Cost comparison of wired and wireless sensor systems for 1) a 30-sensor in-building temperature sensor network and 2) monitoring of three packaged rooftop HVAC systems.*

The wireless system for this in-building temperature sensor application is about 5% less expensive than a wired solution. The estimates in *Table 1* have considerable uncertainties in the assumptions for the installer markup for the wireless system and the wiring cost for the comparable wired-system layout for the demonstration building. The results of this comparison suggest that the wireless system can be a cost-effective solution. In practice, such a wireless system may range from being cost-effective to marginally cost-effective and potentially slightly more expensive than a wired system because of differences in the number of sensors and individual component costs. One of the advantages of the wireless network is that it can be easily extended with additional temperature sensors for the incremental cost of one temperature transmitter. This system can be configured for up to 100 transmitters. Installations with more than 100 temperature sensors require additional receivers and translators.

Rooftop Unit Data Acquisition Example

To compare costs of current technology for wired and wireless data acquisition systems for rooftop packaged HVAC units, we consider an arbitrary rooftop configuration consisting of three separate units, which would require 100 ft (30 m) of wiring and conduit for conventional wired networking. For each unit, four sensors are installed: four temperature sensors (for outside air, return air, mixed air, and supply air) and one indicator of the on/off status of the supply fan. These particular measurements can be used to detect problems with the airside of the units.

Table 1 shows system costs for a wired base case and ranges

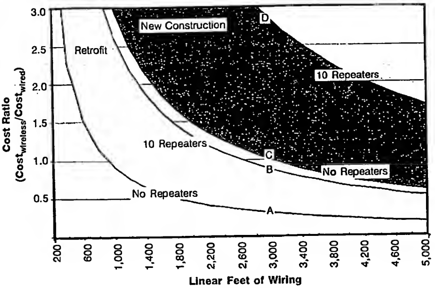


Figure 3: Competitiveness of wireless sensors and data acquisition systems compared to wired systems. Point A (cost ratio=0.3) represents the cost competitiveness of a wireless system in a retrofit case with no repeater necessary. Point B (cost ratio=0.9) represents the cost for a building with high attenuation characteristics, requiring 10 repeaters. Points C (cost ratio=1.0) and D (cost ratio=2.9) represent the corresponding costs for new construction.

of costs for wireless systems configured from commercially available components. Key cost differences between the wired system and the wireless systems are attributable to the communication components. For the wired case, cable and conduit must be installed to each HVAC unit. For wireless systems, that cost is eliminated, but there is the cost of the transmitters and receivers. In addition, laying the conduit and wire generally requires more labor.

The results show that low-cost wireless data collection has cost advantages over wired data collection. High-cost wireless solutions are not cost competitive with wired data collection. These results apply, however, only to the particular configuration chosen. The results illustrate that the cost of the specific wireless system is critical for economic application of wireless data acquisition given today's prices.

Cost Comparison of Wireless and Wired System

We define the cost effectiveness as the ratio of capital cost for a wireless system over the capital cost of a wired system ($Cost_{wireless}/Cost_{wired}$). A ratio of less than unity indicates that wireless technology is more cost effective.

The cost of the *wired* system depends primarily on two key factors: 1) the degree of difficulty to route the wires and to meet code requirements prescribing shielding and wire support and 2) the distance. In general, the installation of wiring in new construction is less difficult because of the relatively easy accessibility to routing channels.

The key drivers for the cost of *wireless* systems are the signal attenuation and signal to noise ratio for the transmission. In general, the higher the attenuation is in a building, the greater the number of repeaters required. We estimated the cost for integrating wireless sensor systems into a wired building automation system (or DDC system) at $500.

The cost-effectiveness ratio ($Cost_{wireless}/Cost_{wired}$) is then a function of distance, installation type (retrofit vs. new construction), and number of repeaters. *Figure 3* shows this relation. Points A, B, C, and D in *Figure 3* represent different cost ratios at a constant length of 3,000 ft for the wiring. For the retrofit example, we establish a wiring cost of $6,600, assuming a cost per linear foot of $2.20 including wires. For new construction, we assumed a reduced wiring cost (because of easier access) in the amount of $2,010 for a cost of $0.67 per linear foot. For the wired system, we assume that wiring conduits already exist and thus, the wiring cost excludes the cost associated with installing conduits. Point A (cost ratio=0.3) represents the cost competitiveness of a wireless system for a retrofit with no repeater necessary. Point B (cost ratio=0.9) represents the cost for a building with high attenuation characteristics, requiring 10 repeaters. Corresponding costs for new construction are represented by Points C (cost ratio=1.0) and D (cost ratio=2.9).

While this cost-effectiveness analysis is simplified, it illustrates the sensitivity to key drivers for wireless technologies in HVAC applications. It indicates that early adopters of this technology most likely will implement wireless devices in existing buildings that do not pose difficulty in transmission of the RF signal. Likely applications include rooftop connectivity with line-of-sight transmission and applications in light construction that do not require repeaters. Wireless technologies in new construction are not yet commonly competitive. Solely battery-operated wireless sensors currently do not achieve the performance of wired sensors with respect to update frequencies. With lower costs for wireless technology and increased availability of products for interconnecting wireless with wired systems, wireless technologies may become an attractive solution for coexisting with and augmenting wired HVAC control networks.

Using Wireless Sensors for HVAC

This section provides some practical tips for adopting wire-

less technologies for buildings. with some specific recommendations for rooftop and in-building applications.

General

• Wireless product offerings are available, and new products are emerging. Search the World Wide Web (e.g., for wireless sensors, wireless HVAC, wireless control) to find available products.

• Costs vary broadly, and specific component or system choices can affect greatly whether the wireless altemative is cost competitive with a wired system.

• Few wireless systems provide products for integrating wireless sensor networks with commonly used HVAC DDC and building automation systems (BASs), but some are beginning to emerge. Ask your controls vendor about wireless technology; some offer it directly.

• Wireless technology costs are likely to decrease with more market penetration. We are expecting greater price reductions in wireless technology than what is common in the rest of the DDC industry.

In-Building Applications

• Consider investing in a wireless network that covers the entire building. Once you have a wireless network, the incremental cost of additional sensors is only the cost of the sensor with little setup cost.

• Integration into existing DDC systems is necessary to use sensor data for controls in a DDC system. Find out what data items are transported from the wireless into the wired system. For instance, for battery-powered transmitters, are low-battery indications reported to the wired system and integrated into the alarm features of the existing DDC system? Particularly if there are hundreds of battery-powered sensor nodes, low-battery alarming is important for maintaining the wireless sensors.

• Inquire about extendability of the wireless network. As the building undergoes internal changes, an additional repeater may be needed to cover newly constructed space. Wireless technologies should be easily extendable by adding additional repeaters and sensors with minimal setup.

• Consider using wireless data collection first for applications where the cost of wired data collection is high. This is likely in existing buildings, where installation of wiring is expensive (e.g., it requires running wiring in conduits on the surface of walls or opening up existing walls).

• Storage buildings that do not have their own BASs but that need to be monitored are candidates for wirelessly connecting to the BAS in a nearby building or at least monitoring in the control of a nearby building.

• Batteries in battery-powered transmitters need to be replaced periodically. Battery life may be five to 10 years, depending on the frequency of transmission. Although low in some cases, this cost should not be neglected in evaluating wireless sensing as an altemative to wired.

• Sensors mounted using Velcro or double-sided tape can be moved by occupants. The authors have not encountered this problem, but it is a possibility. Where this is a concern, more permanent mounting techniques should be considered.

Rooftop Unit Applications

• Determine objectives before laying out the wireless system. Are you collecting data to monitor performance of the unit, looking for faults in components, or providing control? Select sensors and components accordingly.

• Select the wireless components carefully to match the needs of the application, the environment in which the system will be installed, and consider component costs.

• Consider future expansion of your wireless networks and make sure that additional rooftop units can be added to the wireless network without redesigning the entire network.

• Ask the vendor, when possible, to conduct a field strength survey to enable you to select optimal positions for antennas and repeaters.

• Find someone experienced in design and installation of similar wireless installations to design the system for your consideration.

Other HVAC Applications

• Temporarily installed sensors can be used to diagnose suspected problems or occupant complaints. If a wireless sensor network is already installed, adding sensors is easy and inexpensive.

• Wireless sensors can be installed temporarily during system and equipment commissioning to provide data at potentially lower cost than wired sensors. After commissioning is complete, these sensors can be removed for reuse at other sites.

• Temporary addition of a wireless sensor near an existing sensor can be used to check the performance of an existing sensor to determine whether it needs to be recalibrated or replaced.

• Wireless sensors can be removed easily and updated upon failure or when a better sensor becomes available in the future.

• Additional types of sensors can be added to a wireless sensor network without running wire and conduit. For example, wireless CO_2 sensors might be added for a retrofit of demand-controlled ventilation.

Future Trends

While the mobility feature in conventional commercial HVAC control applications may remain limited, at least for the short-term, the cost avoidance for wiring likely will be the key selling point of wireless technology. The earliest adoption of wireless technology is expected to occur in retrofit applications, where the technology extends existing wired control networks to places where there are no control-network cables. This includes, for instance, opportunities for one-way or two-way connectivity among packaged rooftop

units with line-of-sight transmission, permanent or temporary indoor-air monitoring, monitoring of remote equipment (e.g., water pumps, cooling intake valves), and control of outdoor lighting.

The first wireless installations are expected to be monitoring applications that are not time critical and require only one-way communication. Control applications are likely to be limited initially to open-loop control functions, such as turning equipment on or off. Some closed-loop control applications are compatible with current wireless communication; others requiring high update frequencies (e.g., less than a second) pose higher transmission robustness requirements and, therefore, are particularly incompatible with current battery- powered wireless sensing. This presents a challenge for future development. Primary drivers of cost reductions will be optimization of design and manufacturing of RF technology components and further integration of sensing, signal conditioning, and RF communication modules so they can be mass manufactured at lower cost.

Technological challenges for closed-loop control applications with high update frequency requirements still remain for battery-powered devices requiring technological advancements in power management, ultra-low power electronics, and usage of ambient power sources and power scavenging.

As with the advent of television (when many feared it would replace radio broadcasting), it is unlikely that wireless technology will replace wired HVAC controls. A more likely scenario is that it will complement the conventional wired controls technology where it makes economic sense. Significant reductions in cost for wireless sensing will lead to greater use of sensors in building applications, which in turn will lead to better control and maintenance of systems that will improve the overall energy efficiency of the building stock and provide healthier and more productive workplaces.

Acknowledgments

The information reported in this paper was developed under a project sponsored by the Office of Building Technology Programs, Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy.

Inovonics Wireless Corporation played a key role in the work reported in this paper by providing hardware and technical expertise for the in-building wireless demonstration.

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3. RS Means. 2001. *Electrical Cost Data 2001*. 24th Annual Edition, Wiring Methods, 500-7400. RS Means Company, Kingston, Mass.●

Advertisement in the print edition formerly in this space.

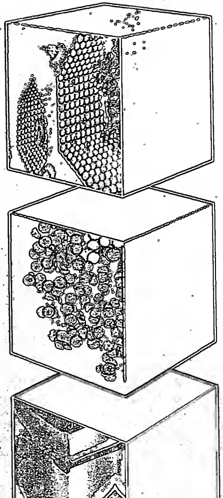
Attachment 2

Pacific Northwest National Laboratory

Laboratory Directed Research and Development

ANNUAL REPORT 2002

Prepared for the U.S. Department of Energy



Sensor Power from Ambient Energy

John G. Desteese, Larry C. Olsen

Funding Profile

FY 2001 Cost: $29.9K
FY 2002 Cost: $65.0K

This project will investigate the feasibility of constructing a power source for small portable electrical devices that will convert heat energy from the environment into electricity. This power source could serve as a "lifetime battery" for small electrical sensors and other devices.

Project Description

Performance and life of wireless electrical devices are typically limited by the operating characteristics of the batteries or other stand-alone power supplies they require. Even where grid connections are possible, the complexity and cost of the necessary wiring prohibit many applications. The concept under development eliminates such constraints by converting heat energy of the environment directly into electricity as an integral function of the device. This project investigates the feasibility of constructing an ambient energy harvesting and conversion device incorporating a miniature thermoelectric generator and an associated heat management system to power small electrical devices. A further developed version of the expected product would be able to power electrical loads in the 50-microwatt to 500-milliwatt range at 3 to 12 volts. This level of power demand is typical of many small sensors, remote monitoring and surveillance devices, actuators, and other lower-power programmable appliances. The proposed concept converts ambient heat into electricity and exploits natural temperature differences in the air or any media surrounding the application. Such a product would enable the lifetime deployment of ambient-powered applications for unattended operation in remote areas without the need for maintenance and connections to an electrical supply or other logistic support. The concept also has application potential as a means of powering wireless sensors and diagnostic devices in energy-smart buildings.

Introduction

The objective of this work is to develop proof-of-concept experiments to demonstrate that direct conversion of thermal energy associated with naturally occurring ambient temperature differences into electric energy could provide perpetual power for sensors and remote devices. For several years, we have recognized the potential of scavenging free energy from ambient sources to energize devices with modest electric power demands. We have evaluated many sources of ambient energy including radio waves, electric power lines, wind, water solar, and human power (De Steese et al. 2000). These studies have led to the design of miniature power generation and storage packages with electric output levels ranging from microwatts to hundreds of watts. Recently, our scientists realized that a conventional thermoelectric generator could be configured to exploit the nearly perpetual difference of temperature that exists across some boundaries (between earth and ambient air, and inside and outside heating, ventilation, and air-conditioning ducts in buildings). In these environments, the characteristically low efficiency of thermoelectric concepts can be tolerated because the heat capability of the source is essentially infinite compared to the relatively small amount of electric energy required for microwatt- to milliwatt-level power applications.

Results and Accomplishments

Effort in FY 2002 focused on the development and demonstration of a breadboard assembly representing a complete ambient-powered sensor system. This assembly comprised the thermoelectric generator, heat management subsystem, power conditioning electronics, sensor, and radio frequency transmitter. These system components were developed and demonstrated in the laboratory and in an outdoor environment. Figure 1 is a block diagram showing the components of the system and the three independent development phases employed.

The interfaces between the thermoelectric generator and the sensor were engineered in the laboratory as represented in Configuration a of Figure 1. In this step, ambient heat input to the thermoelement was simulated using a hot-air gun for convenience. Under simulated ambient conditions, the intrinsic voltage output of the thermoelectric device is only a few hundred millivolts. This voltage must be amplified to at least 3.6 V corresponding to the voltage normally supplied by a lithium battery to power the radio frequency components. Because the thermoelectric output voltage is too low to activate silicon-based electronic power conditioning, a voltage amplifier using germanium transistors was employed to provide a 4.2-V output to the balance of the system. A supercapacitor was introduced to store energy so that the radio frequency stage would operate regardless of fluctuations in ambient conditions that affect the output of the thermoelectric converter. The final element in this test assembly was a resistive load box used to simulate the energy drain required to operate the sensor and radio frequency tag. This load was manually switched on for periods of about 10 seconds at a frequency representing the transmission cycle of the radio frequency tag to drain the equivalent of the total sleep-mode, data acquisition and storage, and transmission energy consumed in each cycle. By respectively heating and cooling the hot and cold shoes of the thermoelectric converter and applying the load periodically as indicated above, the thermoelectric generator was shown to be capable of maintaining capacitor voltage and thereby supplying the energy drain of a simulated temperature sensor and radio frequency tag that transmitted data every 10 minutes.

The balance of the system was developed as shown in Configuration b of Figure 1. In this setup, a conventional regulated laboratory power supply was substituted for the thermoelectric converter and voltage amplifier to permit customizing the sensor and radio frequency subsystem. The sensor and transmitter were adapted from a Pacific Northwest National Laboratory-developed radio frequency tag that measures, stores, and transmits environmental temperature and shock data. The tag was modified to retain only the temperature measurement function and was reprogrammed to draw less energy than its unmodified counterpart. A voltage regulator circuit was added to prevent draining the capacitor to a voltage that would be too low to maintain microprocessor function. An external switch was added to isolate the battery normally required to operate the radio frequency tag. The tag includes a microprocessor that must be programmed before operation. The battery is needed to maintain the program whenever the power supply or the thermoelectric element is not connected. Testing this configuration involved first using the battery to "launch" the program, then isolating it after power was available from the alternative source. A remotely located receiver was used to confirm data transmission. The test sequence using Configuration b established that full functionality of the sensor and radio frequency stage could be maintained when the laboratory power supply provided an input to the supercapacitor equivalent to the thermoelectric output characteristics measured with Configuration a.

The complete system concept was demonstrated in the laboratory and in an outdoor environment using Configuration a and the combination of Configurations a and b as indicated by the jumper connection from the voltage amplifier in a to the supercapacitor in b. Figure 2 displays supercapacitor voltage plotted against time measured with Configuration a outdoors with solar input to the hot shoe of the thermoelectric generator and a heat sink in earth connected to the cold shoe. These records show the ability of the thermoelectric generator to recharge the supercapacitor (i.e., maintain a voltage in excess of 3.6 V) if a temperature difference greater than about 7°C exists across the device. At the same time, the capacitor is

supplying the demand of the sensor and radio frequency tag system transmitting data every 10 minutes. Failure to recharge the capacitor was evident when the temperature differential was less, as illustrated by the record at 4°C. The voltage steps at 10-minute intervals shown by the successful recharge characteristics represent the approximately 20-mJ energy drain associated with the evaluated load cycle. The 9.9°C record shows the concept's ability to ride through variability in ambient energy input as illustrated by the slower rate of recharge during a 10-minute interval (between 30 and 40 minutes) when clouds temporarily reduced solar energy input.

Summary and Conclusions

A complete system breadboard that validated the concept and achieved the other objectives of this work was developed and successfully demonstrated in FY 2002. The effort confirmed indications obtained earlier in the project that thermal energy can be readily harvested from a natural environment and converted thermoelectrically into a maintenance-free and perpetual source of power for small electrical appliances. These include sensors, radio frequency tags and transmitters, remote monitoring/surveillance devices and actuators, and other low-power programmable appliances requiring power in the range from tens of microwatts to hundreds of milliwatts. The breadboard system contained all the components needed in a fully functional system including the provision for energy storage to compensate the variability of ambient conditions. This work provided insights into the design and development of derivative thermoelectric energy harvesting systems that can be simpler, more compact, and inexpensive to manufacture.

Reference

De Steese JG, DJ Hammerstrom, and LA Schienbein. 2000. *Electric Power from Ambient Energy Sources*. PNNL-13336, Pacific Northwest National Laboratory, Richland, Washington.

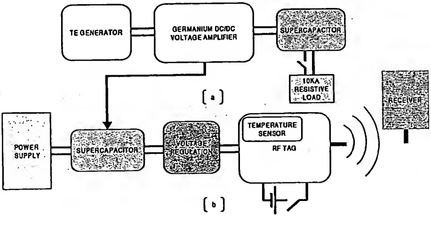


Figure 1. Component and test configurations

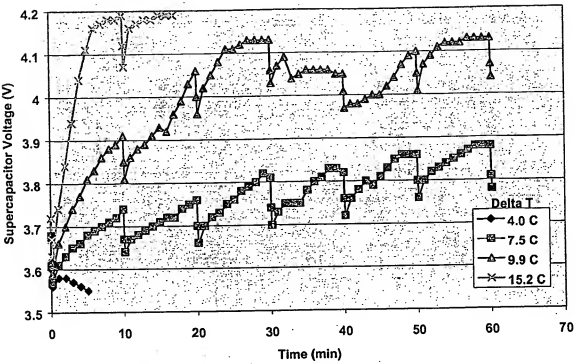


Figure 2. Solar-heated 40-mm Bi-Te thermoelectric generator sustaining supercapacitor charge under simulated 10-minute load cycle conditions

Attachment 3

Sensor Power from Ambient Energy

John De Steese, Larry Olsen, Tim Peters, Jim Skorpik and Juan Valencia

Battelle Pacific Northwest Division

February 5, 2004

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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

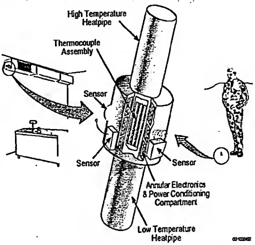
Concept Fundamentals

- Small ambient temperature differences occur spontaneously across natural and artificial boundaries
- Thermoelectric (TE) devices convert heat into electricity and vice versa but are typically too thin to exist in more than a single temperature environment

- Heatpipes connected to a TE converter extend the "reach" of hot and cold shoes to regions of different temperatures
- A small ΔT in a medium with high heat content is sufficient to produce μW's to mW's regardless of TE converter efficiency

Sensors Powered by Ambient Thermal Energy

- Thermal energy scavenged from abundant ambient
- Device is rugged, light weight, suitable for field or facility use
- Perpetual power for life of application
- Independent, maintenance-free electric power for wireless sensing, surveillance, remote actuators and communications



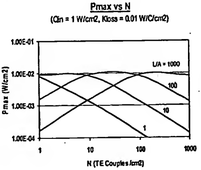
Achievements in 2001

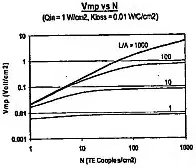
- ▶ Mapped operational regime of Bi-Te converters with incident heat flux up to 10 W/cm^2
- ▶ Assembled and tested heat pipes attached to 40-mm square Bi-Te Melcor elements
- ▶ Demonstrated power output up to 300 μW with $\Delta T < 6°C$
- ▶ Measurable power demonstrated from in-ground deployment simulation

Achievements in 2002

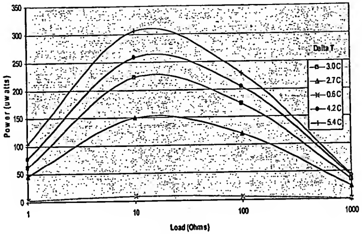
- Investigated L/A advantages with commercial converters
- Demonstrated TE generator/dc-dc inverter interface
- Adapted rf tag to provide balance of system
- Developed and demonstrated integrated system in the laboratory
- Demonstrated power generation in natural environment

Bi-Te Performance Maps for Q_{in}= 1W/cm^2





Test with Noren Products Heatpipes and Melcor 40-mm Bi-Te Thermoelement



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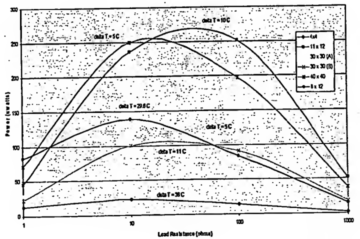
Test with Noren Products Heatpipes and Different Bi-Te Thermoelements



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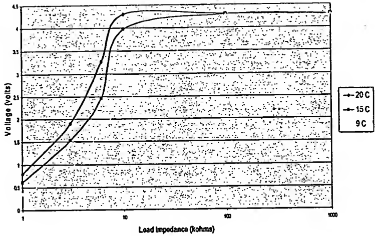
Voltage vs. Load for 11 x 12 mm Bi-Te Element with Germanium DC/DC Converter



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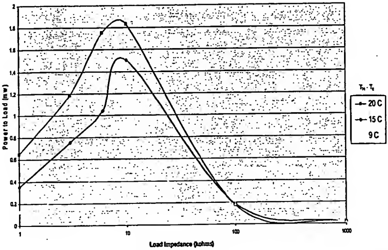
Power to Load from 11 x 12 mm Bi-Te Element with Germanium DC/DC Converter



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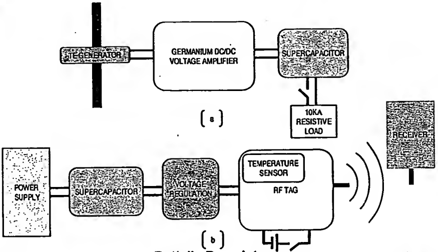
Laboratory Development and Demonstration



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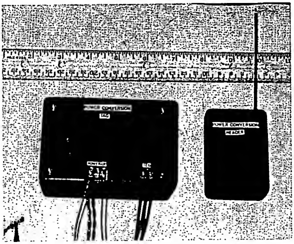
Electronic Packages Closed



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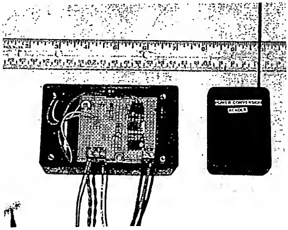
View Inside Box Containing Voltage Inverter, Regulator, RF Tag, Sensor and Transmitter



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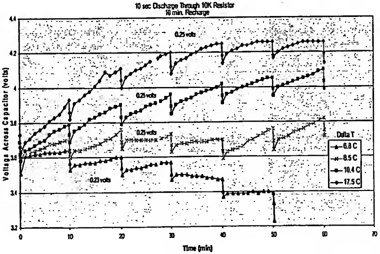
Laboratory Charge Sustainability Test



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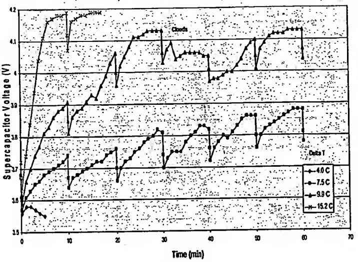
Charge Sustainability Demonstration with Solar Heating and Earth Sink



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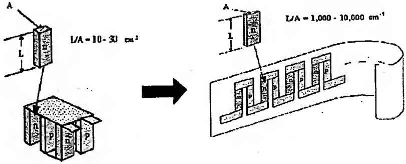
Concept Development



TE Module With Discreet Elements

Thin-Film TE Array

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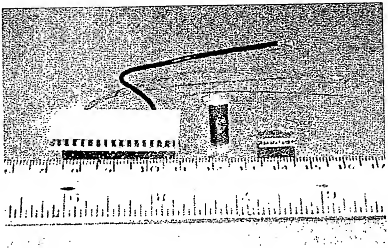
Size Comparison Between Thin-Film and Discrete Element TE Generators



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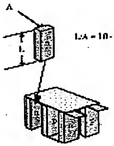
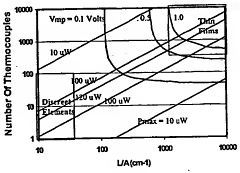
Influence of L/A Ratio



NTE VS L/A For Qin = 0.1 W



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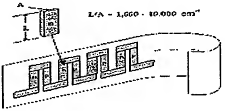
Thin Film Semiconductors For TE Power Generation

Approach

- Sputter Deposit Bi_2Te_3/Sb_2Te_3 Alloys on Plastic
- Have Developed Processes for N- and P-Type Films
- Fabricated Two Prototypes for Ambient Energy Applications



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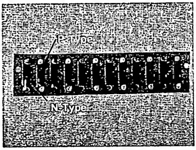
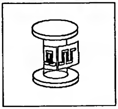
First Generation System

- BiTe-SbTe array deposited by RF magnetron sputtering
- Both N- and P- thermoelements are 1.5 mm wide, 1 cm in length and 2 μm thick
- First generation involved deposition of 6 thermocouples on 2-inch strips of plastic





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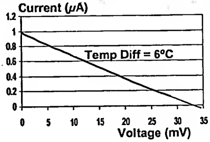
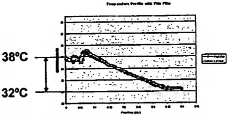
First Generation (Cont)

- Temperature distribution determined with IR Camera
- Measurement of temperature difference across TE elements established performance was as predicted
- <u>18 Thermocouples</u> with $\Delta T = 6\ ^{\circ}C$ Gave $V_{oc} = 33.0$ mV - thus each thermocouple provided 0.305 mV



ΔT = 6°C



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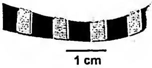
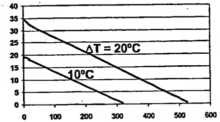
Second Generation Device

- Adjusted film dimensions to achieve larger current and voltage
- Prototype used 14 strips of 9 thermocouples - <u>126 TCs</u>
- Element lengths are 7.4 mm, P- and N- widths are 3.2 mm and 5.3 mm, respectively





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PNNL Programs In Thermoelectrics

DOE Program

Title: Process Scale-Up For High Efficiency TE Superlattices

Objectives: Develop Approach For Sputter Deposition Of Si/SiGe And Other Superlattices At Low Cost And High Volume

Other Activity

- Use Thin Film Bi-Te/Sb-Te Materials To Fabricate Low Power Batteries
- Investigate Use Of Thin-Film TE Materials For Cooling Silicon Microelectronics

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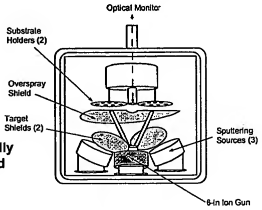
Approach To Sputtering Thin Films

- Have several 1-m box chambers for RF magnetron sputtering
- Can deposit from 3 targets simultaneously or sequentially to form alloys or multilayered film structures



(Front View)

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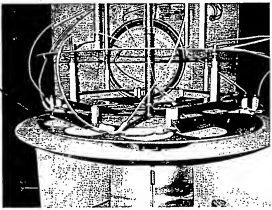
Approaches To Scale-Up

- Platform holds 8 4-inch Si wafers
- Platform rotates over target(s)



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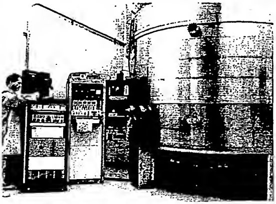
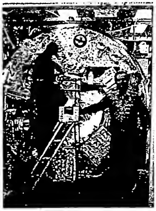
Approaches To Scale-Up (Cont.)

Large 3-meter sputtering chamber



Roll coater



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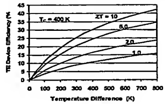
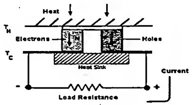
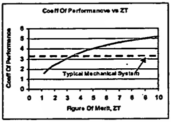
Thermoelectrics: Approach/State-Of-Art

- Convert Heat Directly To Electrical Power With P- And N-Type Semiconductors
- Key Parameter Is Figure-Of-Merit:
  $ZT = S^2\sigma T/\kappa$ (Dimensionless)
- Advanced TE Materials Will Allow Production Of Microwatts To Kilowatts With Efficiencies > 15%



Basic TE Device





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Thermoelectric Figure of Merit

- The Figure-Of-Merit (ZT) was essentially pegged at ~ 1.0 from 1960 to 1995
- Since 1995, ZT values have been estimated for thin film materials to be significantly greater than 1.0

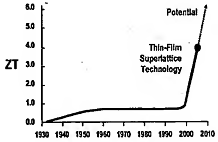

Figure Of Merit Improvement with Time

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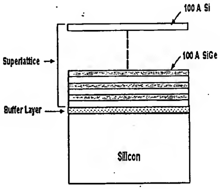
Scale Up Based on DOE Program

- Have developed approach to sputter deposit Si/SiGe superlattices
- Approach developed to grow structures rapidly and on 12 3-inch Si wafers simultaneously
- Films exhibit good TE properties



Si/SiGe Superlattice On Silicon

Attachment 4

SOW for Building Technology Project
For U.S. Department of Energy
Commercial Buildings Program Manager: D. Hansen

Technology Development: Wireless Sensors and Controls

2003/2004 Statement of Work
Pacific Northwest National Laboratory

Michael Brambley, Principal Investigator

December 1, 2003

Fiscal Year	Total Project Funding - 4 Tasks
FY '04	$320K

Task 1: Wireless Monitoring and Diagnostics: Low-Cost Wireless Current and Power Sensors

Funding

Fiscal Year	DOE Funding	SCE Funding	SCE In-Kind
FY04	$70K	$75K	TBD*

*To be determined.

Background

Objective: The objective of this project is to develop and field demonstrate low-cost wireless current and power sensors. The project extends the project started in FY03, which developed and demonstrated a wireless sensor for single-phase power measurement. The single-phase meter prototyped in FY03 will be field tested in collaboration with a large utility company. A wireless electrical power and current sensor for 3-phase power will be designed, built, and tested, also in collaboration with the utility.

Motivation: Energy audits and commissioning of buildings and facilities, fault detection and diagnostic (FDD) tools, as well as advanced controls for optimal energy efficiency operations and load responsiveness require information about power consumption of electricity-consuming equipment. Facility and building managers in the past have been reluctant to invest in power meters because of their high installed cost. This task will address this impediment to the deployment of end-use metering, automated diagnostics, and advanced controls by designing, building, and testing prototypes of a low-cost wireless power meter and a low-cost wireless current transducer.

Availability of inexpensive current and power sensors that can be monitored centrally (e.g., in a control room) will enable measurement of electrical loads in commercial buildings cost effectively. This technology will enable billing of individual tenants for excessive power consumption, enable real-time monitoring of electrical power end-uses, and provide a basis for automated monitoring and diagnostics, which will then lead to more efficient building operation. Three-phase power is commonly used in commercial buildings for equipment of higher power ratings, such as packaged HVAC units, chillers, fans, and pump motors. Currently-available meters used for end-use metering in buildings are too expensive to install, generally require visual inspection to collect data, and are used infrequently and only for a small number of loads, thus a need exists for low-cost, easy-to-install, easy-to-monitor, sensors specifically for 3-phase power.

Furthermore, some utilities have equipment loaning programs that enable commercial and industrial customers to monitor electricity use over a few-week period. Customers have difficulty installing conventional monitoring and logging devices. Wireless monitoring shows the potential to simplify the installation process for utility customers borrowing equipment. Another problem found in such equipment loan programs is the poor condition in which equipment is often returned. Wires can be a tangled mess and sometimes equipment is damaged. By eliminating the wires, one of these problems can be prevented. By ruggedizing, equipment damage could also be reduced. Southern California Edison (SCE) has indicated an interest in collaborating with DOE and PNNL on this project, providing funding and in-kind contributions to support developing the software and field testing the resulting technology. The software will help users with installation of wireless end-use power monitoring hardware and enable display/use of the collected data. If the technology satisfies SCE's performance needs in the field, the company would likely become the first major user of it.

Attachment 5

Thermoelectric Ambient Energy Harvester

A White Paper for the Defense Logistics Agency

John G. De Steese
Pacific Northwest National Laboratory

Abstract

The product of this effort will be a nominally 330-μW thermoelectric (TE) battery with a direct current (DC) output of at least 100 μA at 3.3 V. This output will be achieved with a temperature differential of 20ºC or less when the device is deployed to harvest thermal energy from a natural environment. The specific deployment orientation will be with the hot side receiving heat from free air and sunlight, and the cold side coupled to dry soil as deep as 20 cm. This device will employ novel, PNNL-developed, thin-film TE elements that develop volt-level outputs directly without electronic power conditioning.

Background

For several years, PNNL has explored the potential of scavenging free energy from ambient sources to energize devices with modest electric power demands. Many sources of ambient energy have been assessed including radio waves, electric power lines, and wind, water, solar and human power (De Steese et al. 2000). These evaluations led to the design of ambient energy conversion and storage devices with electric output levels ranging from microwatts to 100's of watts. The resulting PNNL invention combines a novel TE generator with one or more heat pipes to exploit the free thermal energy that is harvestable as a result of spontaneous temperature differences occurring across various boundaries. The normal temperature differences that exist, for example, between earth and ambient air, and inside and outside HVAC ducts in buildings present opportunities to apply this concept. In these environments, the characteristically low efficiency of TE converters can be tolerated. This is because the heat supply capability of the source is usually very large compared to the typically small amount of electric energy required for powering applications such as sensors, small transmitters and monitoring equipment.

Objective

The objective of this work is to assemble a package that integrates a small TE generator with heat-gathering and -rejecting subsystems that exploit natural temperature differences that exist between free air and in-soil environments.

Technical Description

Basic components of this device are heat pipes that couple the hot and cold shoes of a TE battery to ambient heat sources existing at different temperatures either side of a barrier or boundary. In this case, the boundary between zones of

different temperature is the earth's surface. The upper heat pipe communicates thermal energy harvested from free air to the hot shoe of the TE converter. The lower heat pipe conducts waste thermal energy to the heat sink provided by underlying soil.

In general, this concept produces a useful output bi-directionally; i.e., both when the air is hotter than the soil and vice versa. The double heat pipe design is particularly useful if the device is operated in the bi-directional mode, especially when the soil is warmer than the air. In this case, both heat pipes operate as reflux boilers to pump thermal energy upwards through the TE converter and can exploit gravity-assisted return of internal working fluid to their respective evaporator sections.

The specified operational mode addressed in this white paper is harvesting energy from ambient air and conducting it downward through the TE converter to an underground heat sink. This requirement will allow the simplification of replacing the upper heat pipe with a thermally absorptive hot shoe extension. However, fluid flow in the lower heat pipe results from evaporation at the underside of the TE cold shoe and condensation at the lower extremity of the heat pipe where heat is given up to the soil. Re-circulation of the working fluid in this mode of operation requires a wick structure on the inside of the pipe to draw the condensate back up to the evaporator region against gravity. The typical limit for this mode is a wicking height of about 20 cm as constrained by the physical properties of conventional heat pipe working fluids.

The thermocouple assembly comprises many thin-film bismuth telluride TE elements deposited on a flexible substrate using proprietary techniques PNNL recently developed (see related experience section). This assembly is in the form of a rolled up strip of thin-film elements wound on a small reel or bobbin that forms the core of the device. The bobbin is approximately 1.6 cm long and less than 1 cm diameter.

The concept is readily scalable to higher power levels by increasing the number of TE elements deposited on the roll. Conceivably many tens of thousands of miniature elements could be incorporated in series and/or series/parallel arrangements to produce device electrical outputs of up to several of watts. Future advances in TE materials may enable overall conversion efficiencies approaching 10% despite the typically small temperature differential used to drive such devices.

The ends of the bobbin are designed to function as the hot and cold shoes of the thermocouple roll. Heat pipes attached at both ends of the bobbin transfer heat through the TE assembly from the air side to the in-soil side of the device. The primary heat pipes are approximately 20 cm long and between 0.3 and 0.6 cm in diameter using water as the working fluid, unless freezing conditions have to be

accommodated. In this case, methanol or one of the other alcohols would be selected.

The outer surfaces of the air-side heat pipe are coated with a material having a highly absorptive surface to maximize collection of solar radiation, as well as sensible heat from the ambient air. Experiments are being conducted to determine whether the heat transfer achieved by the heat pipe is better than a simple hot shoe extension on the air side of the device. Depending on the outcome, a suitably designed and surface-treated hot shoe may be substituted for the air-side heat pipe. This option would have the advantage of reducing the infrared signature of the deployed system. Insulation will be applied to a major portion of the lower heat pipe to prevent heat leakage into it from relatively warmer soil near the surface. This could interfere with the heat transport from the cold shoe to deeper regions in the soil.

The TE device is designed to generate nominally 330-μW of dc power with an output of 100 μA at 3.3 V. PNNL anticipates the successful incorporation of sufficient thin film elements to offer this performance as the raw, unconditioned power of the device when a temperature differential of 20ºC exists across the hot and cold shoes. However, it may be possible to improve aspects of the design, if the unconditioned output is reduced to a lower voltage (e.g., 1 to 2 V). In this case, a lower voltage device would be assembled with a dc/dc inverter to achieve the required 3.3-V output. This inverter would be a silicon-based micro-electronic circuit. It could also incorporate a super-capacitor to provide energy storage to maintain mission functions when the temperature differential across the TE generator is less than 20ºC.

Anticipated Deliverables

The products of the planned effort will be a deployable 300-μW TE generator activated by ambient thermal energy and a report that describes the design, development, construction and testing of the delivered device.

Related Effort

PNNL has been active in the research and development of devices and concepts that harvest ambient energy since 1995 (see reference). A product of recently completed development effort at PNNL is a small TE battery designed to produce 10's of microwatts at interfaces differing in temperature by only a few degrees.

In performing this work, PNNL recognized the value of using TE elements with larger length-to-area ratios. Such a development offers a more efficient TE generator with a higher unconditioned output voltage. PNNL has successfully deposited thin-film thermocouples on flexible substrates and has developed capabilities to package hundreds to thousands of such couples in the space presently occupied by only 10 to 20 conventional elements. PNNL has high confidence that a miniature 330-μW TE generator can be designed and constructed as described, by building on the above experience.

Milestones and Cost

The cost and schedule for this work would be determined after the technical interest of the potential user(s) is established.

More Information

All material contained herein is provided for informational purposes and is not to be made publicly available. Interested parties should contact the author for more information:

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Fax: (509) 375-3614
E-mail: john.desteese@pnl.gov

Reference

De Steese, J. G., D. J. Hammerstrom and L.A. Schienbein. 2000. Electric Power from Ambient Energy Sources. PNNL-13336. Pacific Northwest National Laboratory, Richland, Washington.